91602
new 82-10

ontario hydro
research division

To: J. L. Bender
Manager, Transmission Stations Program
Design & Development Div - Transmission
H9A7

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if

OTTAWA MERIVALE TS - GROUNDING SYSTEM STUDIES

P. Pillai

Tests were conducted at Ottawa Merivale TS under simulated fault conditions to evaluate the grounding system performance. The station ground potential rise, current splits, touch and step potentials, induction on communication cable and soil resistivity at the station were measured. The measured results were found to be within safe limits for an ultimate HV station fault current of 20 kA. Models were developed to generalize the results to include the addition of 500-kV facilities.

1.0 INTRODUCTION

Merivale TS is located in the township of Nepean, south-west from the city of Ottawa. At the time of the tests, the high voltage facilities at the station included four 230-kV overhead lines, one auto transformer rated 250 MVA, 230/115/13.8 kV Yg/Y/Δ, ten 115-kV overhead lines and two transformers rated 6 MVA, 115/8.32 kV, Δ/Yg. The station supplies Nepean Hydro loads through seven 8-kV overhead feeders. The station has a service and storage yard on the east side. There is an open field to the west of the station and a bicycle path runs along the station fence on the south side. The grounding system at the station is characterized by an irregular ground grid mesh and an extensive network of overhead ground wires connected to the station grounding system. Also the area may have other underground services connected to the station ground. This could make design-type calculations of the grounding system performance at the station difficult. Therefore, measurements were done under simulated fault conditions to confirm the adequacy of the grounding system performance for the existing station and with the addition of 500-kV facilities. The project was requested and funded by Design and Development Division - Transmission.

2.0 TEST PROCEDURE

Figure 1 gives a layout of Merivale TS with respect to the grounding tests conducted at the station on April 28 and 29, 1987. The 230-kV line M31A between Merivale TS and Hawthorne TS was taken out of service and the line grounding switch at Hawthorne was closed to sink test current. A test current of 20 A at 120 V, 67 Hz was injected from a gasoline-powered generator into three parallel phases of the test circuit as shown in Figure 2 and the following measurements were made:

(a) Station ground potential rise between a remotely grounded Bell telephone pair towards north and local station ground and between a remotely grounded Ontario Hydro communication pair to Carling TS and local station ground.

(b) A potential profile south-west of the station.

(c) Current splits on skywires, distribution neutrals and transformer neutrals.

(d) Fence potentials and station step and touch potentials.

(e) Induction on a remotely grounded Ontario Hydro communication pair to Albion TS which parallels the test circuit.

(f) Soil resistivity.

Potentials and currents (both magnitude and phase angle) were recorded with respect to 1.0/0 A injected current using an HP3582A network analyzer in conjunction with a differential amplifier. Two Ritz clip-on 5 VA, 150/5 A CTs with 0.66 Ω shunts were used to measure the current signals. Telephone style carbon protectors were used to limit the potential to local ground on the input wiring to the instrumentaion in the event of a system fault. Also heavy connections were made from the frame of the instrumentation to the station ground. A soil resistivity survey using the Wenner method was done on a field north of the station. A Megger DET-2 ground resistance tester was used to take the Wenner readings.

Assistance was obtained from District Operations, Stations and Lines Maintenance, Regional P&C and Transmission Operations in conducting the test.

3.0 TEST RESULTS

3.1 Measured Soil Resistivity

The apparent soil resistivities calculated from the measured Wenner data (equation 7.1 of the Grounding Guide/1/) are given in Table 1 along with a fitted two-layer model parameters.

TABLE 1

MERIVALE TS - SOIL RESISTIVITIES

Probe Spacing (m)	Apparent Resistivity (Ω.m)	
	Measured	Modelled
1	62.2	62.2
2	62.9	62.2
5	63.6	62.5
10	69.3	72.0
20	92.0	92.0
50	141.2	130.0
100	143.3	143.0

Fitted Two-Layer Model Parameters

ρ_1 = 60 (Ω.m)
ρ_2 = 150 (Ω.m)
d = 10 m

3.2 Measured Ground Potential Rise

The potential profile readings were plotted against inverse distance which can then be extrapolated to infinite distance at the origin to give ground potential rise. This assumes uniform soil and point current injection which should be accurate at larger distances. For potentials at rather closer distances, a horizontal rescaling based on an inverse sine method (disk geometry) was used to include proximity of the station /2/.

The ground potential rise measured on the remotely grounded Ontario Hydro communication pair and Bell telephone pair were corrected to take into account an estimated shielding factor of 0.9/-15. Additional correction factors were applied to compensate for induction from the test circuit and the distribution neutrals. The corrected measured results are given in Table 2 along with the modelled value (discussed in section 4). For an ultimate HV fault current of 20 kA, the maximum measured GPR is about 1.4 kV.

TABLE 2

MERIVALE TS - GROUND POTENTIAL RISE (GPR)

GPR From	GPR (mV/A)
(1) Measured Potential Profile	
a) Point Current Injection	65.0/43
b) Disk Geometry	64.0/43
(2) Measured on Hydro Comm. Pair	71.8/10
(3) Measured on Bell Tel. Pair	68.6/7
(4) Modelled	84.0/16

3.3 Measured Touch and Step Potentials

Touch and step potentials were measured at several locations and the worst case is presented in Table 3. A potential of about 0.5/40 mV/A was measured between the station fence and the station ground and about 12.8/47 mV/A was measured between the isolated fence around the service area and the station ground.

TABLE 3

MERIVALE TS - TOUCH AND STEP POTENTIALS

	Measured (mV/A)	Modelled (mV/A)
Station Touch Potential (Mesh Voltage)	1.3/69	8.4/16
Fence Touch Potential		
(a) Outside South Fence	1.7/37	8.1/16
(b) Outside North-East Fence	4.7/30	-
(c) Inside South Fence	0.9/27	-
Station Step Potential	0.3/75	4.5/16

3.4 Measured Induction on Communication Cable

A potential of 286.6/42 mV/A was measured between the local station ground and a remotely grounded communication pair to Albion TS which parallels the test circuit. After subtracting the measured GPR, the longitudinal induced voltage is about 228.9/52 mV/A for an exposure length of about 3.6 km. This is about 4.6 kV for an ultimate HV station fault current of 20 kA. Note that the neutralizing transformers were bypassed for the measurements.

3.5 Measured Current Splits

The measured current splits are given in Table 4 along with modelled values. The "measured" current split in the station ground was estimated by subtracting the measured splits from 1.0/0 A injected current.

TABLE 4

MERIVALE TS - CURRENT SPLITS

Current Path	Measured (A)	Modelled (A)
Injected to M31A Phases	1.00/0	1.00/0
Skywires	0.48/16	0.45/25
Transformer Neutral	0.04/-40	0.04/-40
Distribution Neutrals	0.22/-23	0.34/-45
Station Ground	0.31/-4	0.35/16

4.0 MODELLED RESULTS

4.1 Soil Resistivity

The measured soil resistivity data was interpreted as a two layer model using the method given in Appendix D of the grounding Guide/1/. An equivalent resistivity of 100 Ω.m was derived for the station based on an equivalent station radius of 113 m.

4.2 Isolated Station Ground Resistance

An isolated station ground resistance of 0.24 Ω was calculated based on an equivalent soil resistivity of 100 Ω.m, an estimated station radius of 113 m and 6000 m of buried ground conductors (Equation 3.3 of the Grounding Guide /1/).

4.3 Modelled Current Splits

Figure 3 shows the conductive equivalent circuit with respect to fault current splits for the test conditions. For 115-kV circuits L2M and L1MB to St. Lawrence TS, the skywires were not connected to the station ground and hence were neglected in the model. The conductive circuit impedances were calculated using simplified formulas for Carson's earth return self impedances. The conductive component of the fault current was derived as SI_f where S is the shielding factor calculated from the skywire self and mutual impedances. $(1-S)I_f$ is the inductive component of the skywire split. Appendix A summarizes various formulas used in the calculations.

The skywires are either 42 mm^2 (5/16") or 51 mm^2 (3/8") steel depending on the design. For the skywires in each direction an equivalent conductor earth return self impedance was calculated based on an equivalent geometric mean radius of the skywires. An estimated tower footing resistance of 12 Ω, a ground rod resistance of 34 Ω for the wooden poles, and a span of 300 m were used for calculating the lumped conductive impedance of the skywires in each direction. The net skywire self impedance in all directions was calculated as 0.49/27 Ω and the calculated shielding factor is 0.80/-14.

For the seven 8-kV distribution feeders, a net impedance of 0.245 /61 Ω was calculated based on the parallel combination of the feeders assumed to be grouped in three directions on poles with 85 mm^2 (3/0 AWG) ACSR ground conductors. Distribution taps were assumed at 200 m spacings along the main feeders with the first tap at 500 m from the station and service drops at 20 m spacings, with a ground resistance of 10 Ω due to water pipe connections at each house.

Preliminary calculations gave a neutral impedance of about 2 Ω for the two distribution transformers assuming 100% load on each transformer. This compares reasonably with an impedance of about 1.8 Ω estimated from the measured current split and the GPR. Therefore, the measured current split was used in the model.

The equivalent circuit in Figure 3 was solved for the fault current splits and these are given in Table 4. Note that the total skywire split is the sum of the conductive and inductive components. The interconnected ground impedance at the station was calculated as 0.11/29 Ω.

4.4 Modelled Ground Potential Rise

The station ground potential rise, V_g was calculated as $I_g R_g$ where I_g is the station ground current split and R_g is the station ground resistance. For an ultimate HV fault current of 20 kA, the modelled GPR is about 1.7 kV.

4.5 Modelled Touch and Step Potentials

Table 3 gives the calculated touch and step potentials along with the measured results at the station. The fence touch potential to the public outside the fence was calculated using the equation 3.10 of the Grounding Guide/1/. This formula assumes that the ground grid is made of infinitely long conductors perpendicular to the profile line. Here a distance of 30 m was assumed for the south fence outside the station grid. For an ultimate HV station fault current of 20 kA, the calculated fence touch potential to the public is about 160 V. The station mesh and step voltages were calculated using equation 3.6 of the Grounding Guide/1/ and equation 73 of the IEEE Guide 80/3/ respectively. For the above fault current of 20 kA, these are approximately 170 V and 90 V respectively.

4.6 Modelled Induction On Communication Cable

Induction on the communication cable paralleling the test circuit was calculated using simplified formulas for Carson's earth return mutual impedance (Appendix A). Although the communication cable and the test circuit are non-uniformly spaced, an average separation of 200 m was estimated from drawings. The exposure length was about 3.6 km from Merivale TS to Riverside Road where the communication pair was remotely grounded for measurement. A shielding factor of 0.9/-15 was assumed for the communication cable. This preliminary calculations gave a longitudinal exposure of about 340/24 mV/A which is about 6.8 kV for an ultimate HV station fault current of 20 kA.

5.0 ADDITION OF 500-kV FACILITIES

Two 500-kV lines from Lennox GS to Hawthorne TS will be passing through Merivale TS in the near future. New facilities include a 500-kV double circuit line west towards Lennox GS and two 500/230/115-kV lines east towards Hawthorne TS. The grounding system at Merivale TS and the station fence on the south side will be extended to include the new towers for the above.

The grounding system model described in the previous section was modified to estimate the grounding system performance with the addition of these new facilities. A revised station ground resistance of 0.23 Ω was calculated to include the fence extension on the south side, based on a new grid area of 42,000 mm^2 and 6000 m of buried ground conductors. The calculated equivalent station radius is about 116 m.

With the revised skywire connections to the station ground, their conductive self impedance was reduced to 0.37 /27 Ω. A shielding factor of 0.59/-22 was calculated for a fault on the test circuit. This assumes two 74 mm^2 (7 # 7) aluminum-clad skywires for each new tower line.

The current splits are now 0.25/8 A on the station ground, 0.23/-53 A on the distribution neutrals and 0.62/16 A on the skywires using the revised values for the skywire impedances, station ground resistance and shielding factor in Figure 3. The calculated ground potential rise is about 58.0/8 mV/A which is about 1.4 kV for an ultimate station fault current of 24 kA. The estimated fence touch potential to the public outside is about 5.8/8 mV/A and station touch (mesh) and step potentials are approximately 6.0/8 mV/A and 3.2/8 mV/A respectively. For the above fault current of 24 kA, the fence touch and step station voltages are approximately 140 V and 80 V respectively. These values are all lower than those calculated for the existing station.

6.0 DISCUSSION OF RESULTS

a) The large grid area at Merivale TS resulted in a station ground resistance of 0.24 Ω. The extensive network of skywires along with the distribution neutrals further reduced the interconnected station ground impedance to about 0.11/29 Ω. As a result, the measured and modelled station GPR of about 1.4 kV and 1.7 kV respectively for an ultimate HV fault current of 20 kA are both under the recommended limit of 3 kV.

b) A smaller current split was measured on the distribution neutrals compared to the modelled value probably due to other current paths which were not measured and thus ignored in the model. Therefore, the modelled station ground current and the resulting ground potential rise may be liberal.

c) The potentials measured at several locations between the station fence and the station ground are less than 1 % of the GPR. This confirms that the station fence is connected to the main ground grid as indicated on the station drawings. These measurements were made to local station ground which minimized induction on the test leads.

d) The tolerable limits of touch and step potentials calculated using equations 2.4 and 2.2 of the Grounding Guide/1/ are 179 V and 224 V respectively based on a maximum allowable body current, $I_k = 0.116/\sqrt{t}$ for general population (average 50 kg) standing on the bare soil. For a child weighing 20 kg standing on the bare soil, the tolerable touch and step voltage limits were calculated as 80 V and 190 V respectively based on $I_k = 0.052/\sqrt{t}$ (Figure 4 of IEEE Guide 80/3/). A fault clearing time t of 0.5 second was assumed for the calculations.

e) On the metallic fence on the south side of the station, adjacent to the bicycle path, the measured touch voltage to the public, which is about 34 V for an ultimate HV station fault current of 20 kA, is considerably lower than the tolerable limit. This is mainly due to the metallic gradient control conductor installed along the fence as shown in the station drawings. The modelled value given in Table 3 which is about 160 V for the above fault current is considerably higher than the measured value mainly because the model did not include the gradient control conductor. Also, the model did not take into account the irregularity of the station ground grid. The equations used in calculating the touch, step and mesh potentials apply to uniform ground grid mesh. For the irregular grid layout at Merivale TS, the various parameters in the equations were difficult to estimate accurately. Therefore, the modelled value may not be accurate. Without the gradient control conductor, the touch voltage could have exceeded the tolerable limits for general public. The higher touch voltage measured on the north-east corner of the station fence compared to that measured on the south fence is probably due to lack of a gradient control conductor in this area.

f) The measured and modelled station step and touch (mesh) voltages for the above fault current of 20 kA are both within the tolerable limits. Here also, the model did not take into account the irregularity of the station grid as explained above.

g) The isolated fence enclosing the service area on the east property would rise to about 12.8/47 mV/A as measured. For the above fault current of 20 kA, this is about 260 V which exceeds the tolerable touch voltage limit of 179 V. However, touch hazard is controlled by isolating wooden blocks installed between this fence and the station fence.

h) Preliminary calculations indicated that the station GPR for a LV fault is well under the safe limit of 3 kV. Therefore, a detailed analysis was limited to a HV station fault.

i) The study results should be conservative since the ultimate HV station fault current of 20 kA included a contribution from autotransformers which circulates inside the station. For a fault on a HV line outside the station, the fault current should be limited by line and source impedances to be lower than 20 kA.

k) With the addition of 500 kV facilities, the heavy skywires should improve the fault current shielding factor. The skywires should carry about 62% of the fault current with only about 25% entering the station ground. As a result, the GPR at the station is reduced and is found to be well under the safe limit, for an ultimate HV station fault current of 24 kA. The calculated touch and step potentials are also found to be lower than that for the existing station and are within the tolerable limits for general population, for the above fault current. As seen from the measurements, the touch hazard is considerably reduced for gradient control conductors along the fence and should be within the tolerable limit for a child.

7.0 CONCLUSIONS

a) From the Wenner test data, an equivalent soil resistivity of 100 Ω.m was derived for the station for calculating the station ground resistance.

b) The isolated station ground resistance of 0.24 Ω was estimated from the ground grid geometry. The modelled interconnected station ground impedance is about 0.11 Ω.

c) For an ultimate HV station fault current of 20 kA, the ground potential rise (GPR) at the station is under the safe limit of 3 kV. The maximum measured GPR at the station is about 71.8 mV/A which would be about 1.4 kV for the above fault current. The modelled value is about 84.0 mV/A.

d) The tolerable touch and step voltages for the station were calculated as 179 V and 224 V for general population standing on bare soil and for a child of 20 kg, these are 80 V and 190 V respectively.

e) The measured fence touch potential to the public outside the south station fence is about 1.7 mV/A. This is about 34 V for the above fault current of 20 kA and is well under the tolerable limits.

f) The station step and touch (mesh) potentials for the above fault current of 20 kA are both within the tolerable limits.

g) Measurements confirmed that the station fence is bonded to the main station grid as indicated on the station drawings.

h) A potential of about 12.8 mV/A, which is about 260 V for the above fault current, was measured between the isolated fence enclosing the service area on the east property and the local station ground. However, touch hazard is controlled by the isolating wooden blocks installed between this fence and the station fence.

i) A longitudinal induced voltage of about 220.6 mV/A for an exposure length of approximately 3.6 km (without GPR) was measured on a communication pair to Albion TS paralleling the test circuit. This supports the use of the neutralizing transformers at the station.

j) Based on the model developed, the ground potential rise at Merivale TS with the addition of 500 kV facilities was calculated as 58.0 mV/A which is about 1.4 kV for an ultimate HV station fault current of 24 kA.

k) With the addition of 500 kV facilities, the modelled fence outside touch potential and station touch (mesh) and step potentials are 5.8 mV/A, 6.0 mV/A and 3.2 mV/A respectively. For the above fault current of 24 kA, these are within the tolerable limits for the general population.

Approved:

A.F. Baljet
Manager
Electrical Research Department

Submitted:

P. Pillai
Engineer
System Studies Section

PP:td

REFERENCES

1. Ontario Hydro, Guide for Grounding, 1983 Revision.

2. E.P. Dick, "Modeland TS - Grounding System Resistance and Soil Potential Profile", Ontario Hydro Research Report 82-325-K, February 28, 1983.

3. IEEE Standard 80, IEEE Guide for Safety in AC Substation Grounding, 1986 Revision.

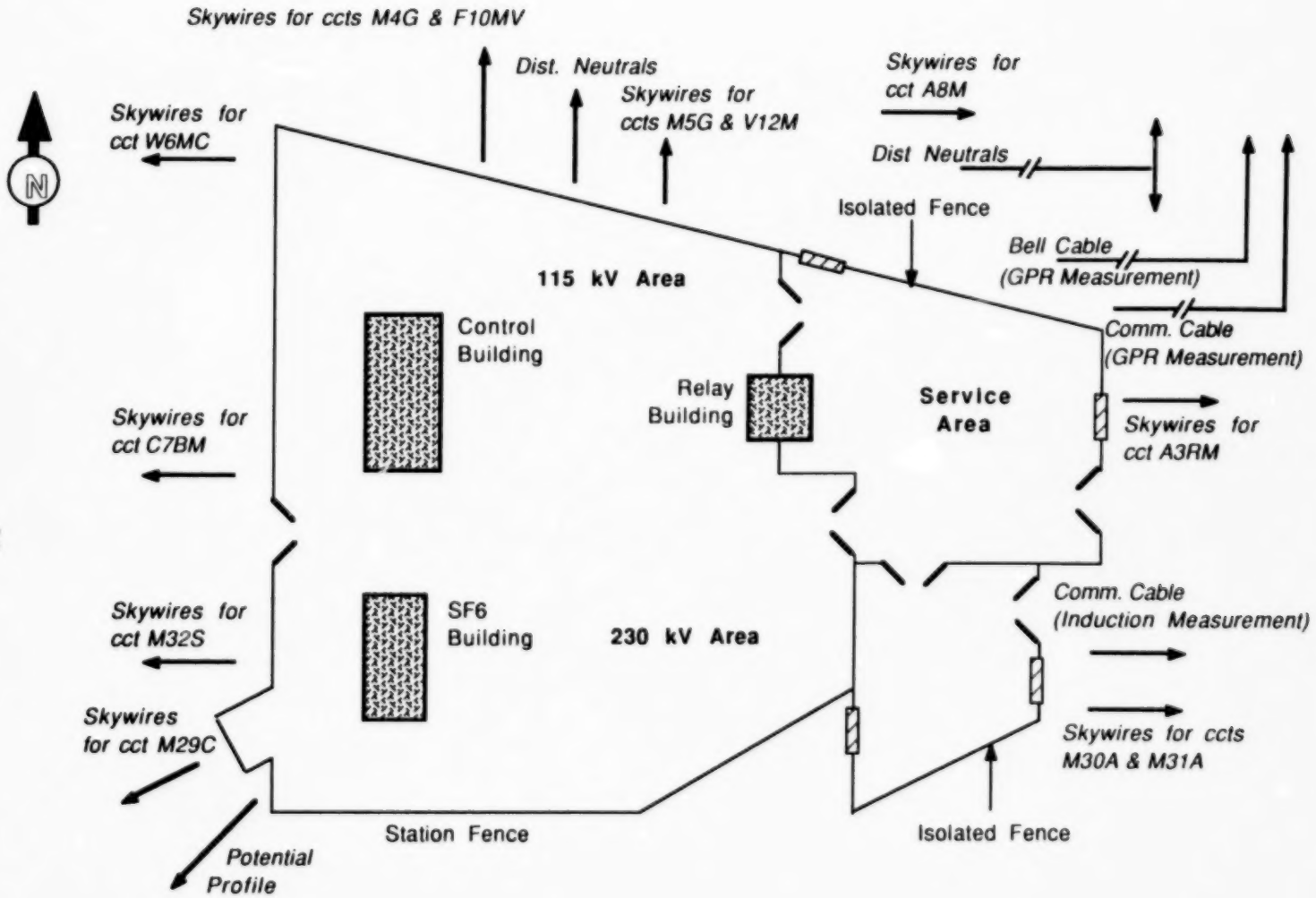

FIGURE 1
OTTAWA MERIVALE TS LAYOUT WITH RESPECT TO GROUNDING TESTS
(Not To Scale)

87-257
175756 RD

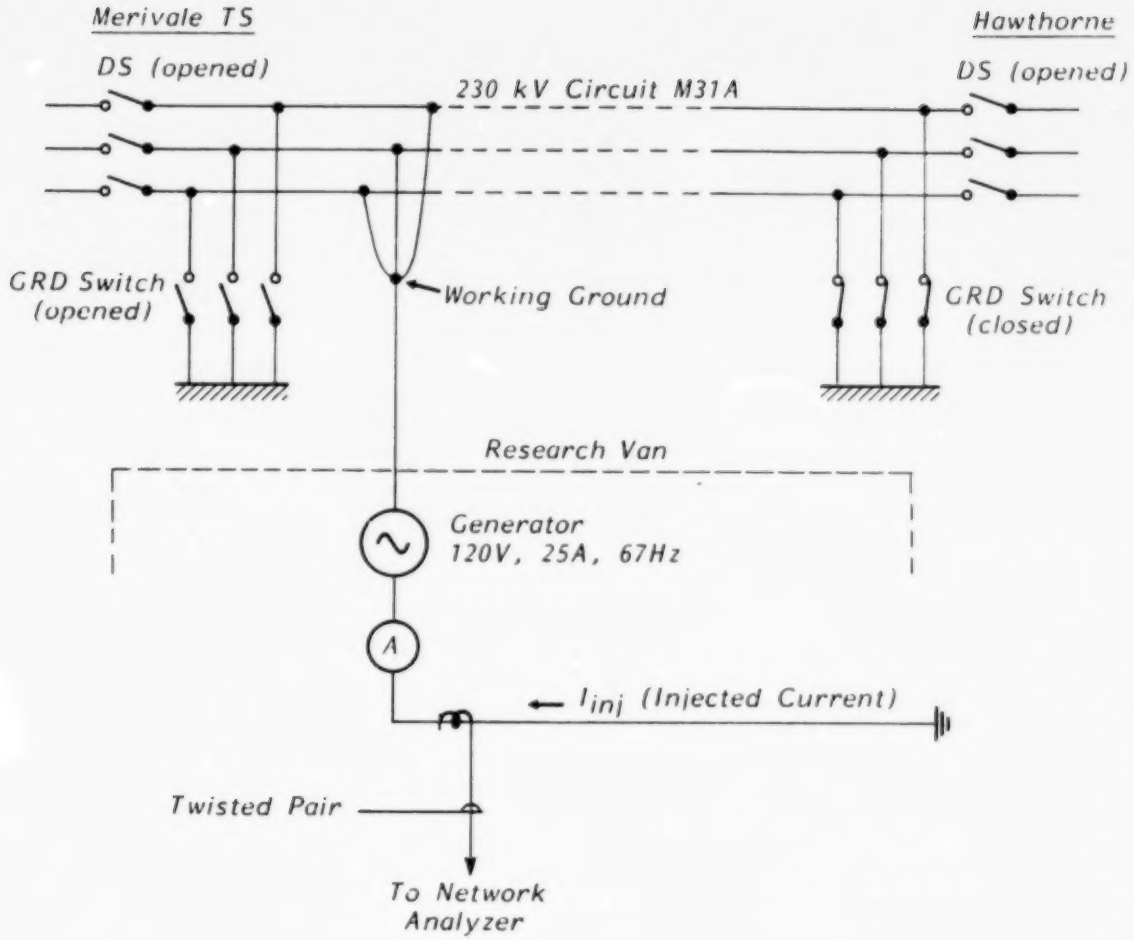

FIGURE 2

OTTAWA MERIVALE TS
GROUNDING TESTS-FAULT SIMULATION CIRCUIT

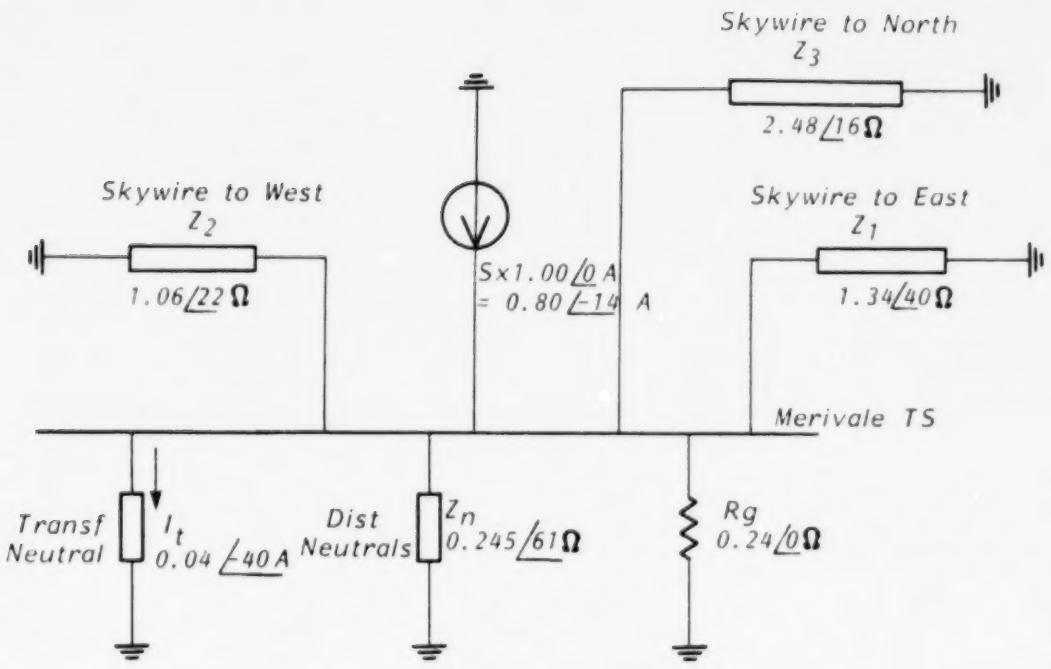

FIGURE 3

OTTAWA MERIVALE TS
CONDUCTIVE EQUIVALENT CIRCUIT FOR HV STATION FAULT

APPENDIX A
SUMMARY OF FORMULAS USED IN GROUNDING CALCULATIONS

1. Conductor Earth Return Self Impedance, Z_s

$$Z_s = R_s + jX_s \ (\Omega/km) \tag{1}$$

$$R_s = 0.059 + R_{ac} \ (\Omega/km) \tag{2}$$

$$X_s = 0.0377 \ln \left(\frac{8440 \ \rho_s}{GMR^2}\right) \ (\Omega/km) \tag{3}$$

Where, R_{ac} = conductor ac resistance (Ω/km)
ρ_s = soil resistivity (Ω.m)
GMR = conductor geometric mean radius (m)

For pipes or shields, R_{ac} and X_{ac} (conductor internal reactance added to X_s) are calculated as shown in reference/3/.

2. Conductor Earth Return Mutual Impedance, Z_m

$$Z_m = R_m + jX_m \ (\Omega/km) \tag{4}$$

$$R_m = 0.0377 \tan^{-1} \left(\frac{8440 \ \rho_s}{GMD^2}\right) \ (\Omega/km) \tag{5}$$

$$X_m = 0.0377 \ln \left(\frac{8440 \ \rho_s}{GMD^2} + 1\right) \ (\Omega/km) \tag{6}$$

Where, ρ_s = soil resistivity (Ω.m)
GMD = geometric mean distance between conductors (m)

3. Tower Footing Resistance, R_t

$$R_t = \frac{\rho_s}{2\pi}\left[\frac{1}{r} + \frac{2.707}{w}\right] \ (\Omega) \qquad (7)$$

Where, ρ_s = soil resistivity (Ω.m)
r = equivalent footing radius (m)
w = footing spacing (m)

4. Chain Impedance of Skywires, Z_c

$$Z_c = \sqrt{Z_s \ell R_t} \ (\Omega) \qquad (8)$$

Where, Z_s = conductor earth return self impedance (Ω/km)
ℓ = span length (km)
R_t = tower footing resistance (Ω)

5. Station Earth Potential to Remote Ground $V_{(x)}$

Refer to /5/.

For disk-like electrode in uniform earth,

$$V_{(x)} = \frac{\rho_s I_g}{2\pi r} \sin^{-1}\left(\frac{r}{x}\right) \qquad (9)$$

Where, ρ_s = soil resistivity (Ω.m)
I_g = ground current (A)
r = station radius (m)
x = distance from station centre (m)

DISTRIBUTION

Mr. J.L. Bender	Des & Dev - Transmission, H9A7
Mr. B.A. Oliver	Des & Dev - Transmission, H9C1
Mr. E.J. Brookland	Des & Dev - Transmission, H9B7
Mr. E.J. Gooch	Des & Dev - Transmission, H9A27
Mr. J.H. Midgley	Des & Dev - Transmission, H8A27
Mrs. A.M. Sahazizian	Des & Dev - Transmission, H8A18
Mr. S.J. Arnot	Des & Dev - Transmission, H8A21
Mr. A. Renzi	Des & Dev - Transmission, H8A22
Mr. G.W. Jackson	Des & Dev - Transmission, H10A19
Mr. L.J. Perfecky	Des & Dev - Transmission, H10A18
Mr. L.V. Doran	Transmission Operations, U9A5
Mr. W.E. Palmer	Transmission Operations, U9A1
Mr. H.H. Tan	Transmission Operations, U9B4
Mr. H.W. Parish	Transmission Operations, U7E5
Mr. J.J. Clifton	Transmission Operations, U7E4
Mr. J.S. Hartill	Transmission Operations, U10A5
Mr. R.H. Cook	Transmission Operations, U10E3
Mr. A.E. Martin	Transmission Operations, U7A1
Mr. L.J. Rubino	System Planning, H4G25
Mr. E.G. Neudorf	System Planning, H4D27
Mr. V.J. Lynch	Eastern Region, Belleville
Mr. M.E. Bedford	Eastern Region, Belleville
Mr. R.T. Anderson	Eastern Region, Belleville
Mr. D. Hoffman	Eastern Region, Belleville
Mr. P.A. Richardson	Eastern Region, Belleville
Mr. R.F. Coghlan	Eastern Region, Ottawa District
Mr. J. White	Eastern Region, Ottawa District
Mr. L.L. Ingratta	Eastern Region, Ottawa District
Mr. J. Hager	Eastern Region, Ottawa District
Mr. A.F. Baljet	Electrical Research
Mr. J.N. Edgar	Electrical Research
Dr. G.L. Ford	Electrical Research
Mr. C.C. Erven	Electrical Research
Mr. D.C. Lee	Electrical Research
Mr. E.P. Dick	Electrical Research
Mr. A. Narang	Electrical Research
Mr. R. Cheung	Electrical Research
Mrs. P. Pillai (2)	Electrical Research

Public Reference Centre
Editorial Section (2)
Office Copies (2)
Extra Copies (3)

- last page -